

Transmission Imaging of Magnetic Domains Using New Circular Polarizing Filter and the STXM

J.B. Kortright,¹ Sang-Koog Kim,^{1,2} and T. Warwick²

¹Materials Sciences Division, Lawrence Berkeley National Laboratory,
University of California, Berkeley, California 94720, USA

²Advanced Light Source, Lawrence Berkeley National Laboratory,
University of California, Berkeley, California 94720, USA

INTRODUCTION

Imaging magnetic domains with soft x-rays offers several complementary features compared to other techniques. Primary among them is the inherent element-specificity resulting from the core level spectroscopies providing magnetic contrast, thus far utilizing the magnetic circular dichroism (MCD) effect. The first domain images using soft x-rays resulted from imaging emitted secondary photo-electrons [1], and photo-electron emission microscopes (PEEMs) continue to be developed with increasing resolution at the ALS and elsewhere [2]. PEEMs necessarily image surface or near-surface magnetic features, with information depth determined by the escape depth of the secondary electrons (several nm, typically). A second type of magnetic microscope operates in transmission, and thus can study magnetization distributions throughout the bulk of thin films. The first transmission imaging of magnetic domains occurred at BESSY using an imaging zone plate microscope [3] and out-of-plane circular polarization from a bending magnet source to produce MCD contrast on transmission through a sample with perpendicular magnetic anisotropy.

We have produced the first magnetic domain images observed at the ALS using a newly developed circular polarizing filter based on resonant magneto-optical effects in conjunction with the scanning transmission x-ray microscope (STXM) on beamline 7.0. Below is first described the circular polarizing filter, and then early images through demagnetized Fe films.

MAGNETO-OPTICAL CIRCULAR POLARIZER USING MCD EFFECT

Our proposal includes two schemes for obtaining magnetic contrast using the linearly polarized undulator illuminating the STXM. One uses a circular polarizer converting linear to circular polarization that then provides MCD contrast in samples having varying magnetization distributions. The other is to sense Faraday rotation through samples using linear polarizers in the transmitted beam [4]. So far only the first approach has been pursued.

Resonant circular polarizing filters using the MCD effect are simple to produce, and operate precisely at those energies required for obtaining MCD contrast in microscopy [5]. Transmission of a linearly polarized beam with wavevector \mathbf{k} through a saturated magnetic film with magnetization \mathbf{M} results in differential absorption of the + and - helicity components that together make up the incident linear beam, resulting in a transmitted beam with net circular polarization whenever $\mathbf{k} \cdot \mathbf{M} \neq 0$. This was characterized for a 48 nm thick Fe film with \mathbf{M} in-plane by varying the incidence angle θ and measuring the polarization of the transmitted beam using a tunable multilayer linear polarizer. The photon energy was tuned precisely to the peak of the L_3 white line, where MCD is maximum. Figure 1 shows how the measured degree of circular polarization P_C^2 varies with θ , which provides the magnitude of the MCD effect as indicated, based on a simple model of in-plane magnetization. The variation with θ of several other quantities is shown in the figure, including the transmission of + and - helical components (T_+ , T_-) relative to their value at 90° , and a figure of merit given by $P_C^2 T$ where T is the average

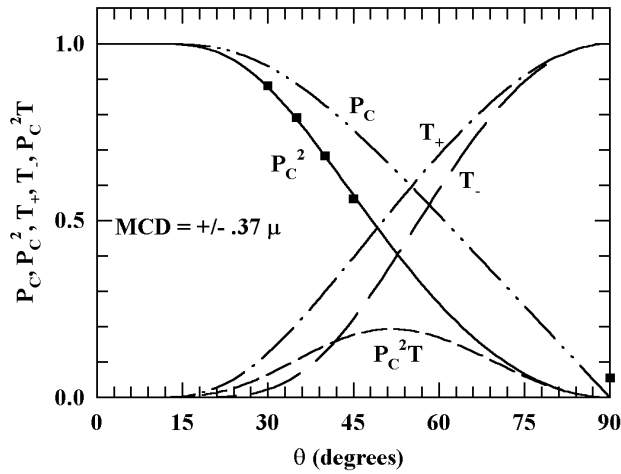


Figure 1. From a linearly polarized incident beam, MCD produces an increasingly circularly polarized transmitted beam as $k \cdot M$ increases (θ decreases). Fits to the measured degree of circular polarization squared, P_C^2 (squares) yield the magnitude of the MCD effect as $\pm .37$ of the polarization averaged absorption at the L_3 white line peak. The various lines use this size of the MCD effect together with a simple model to calculate the transmission of + and - helical components relative to their value at normal incidence, and the figure of merit $P_C^2 T$. See ref. 5 for details.

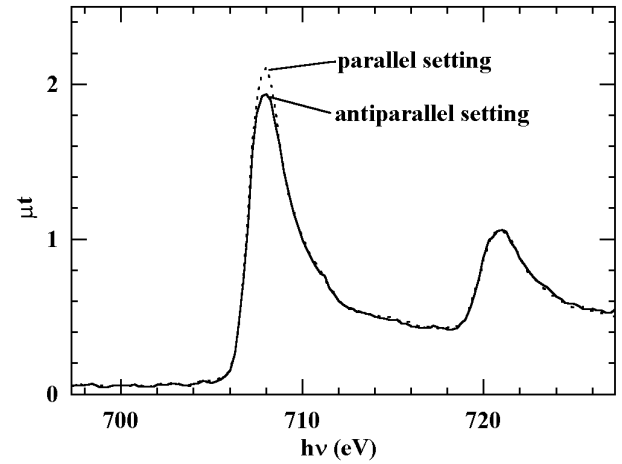


Figure 2. The transmission absorption spectrum from two saturated, 26 nm Fe films, one the circular polarizer and the other the sample, show differences at the L_3 line when M in the two films are nominally parallel and antiparallel to each other. The 15% difference in absorption index in this specific case provides nearly 20% maximum contrast for imaging 180° domains.

of T_+ and T_- . The sense of transmitted helicity can be switched by reversing the sign of M either mechanically or electromagnetically. More details on this new type of circular polarizer, which is the first use of magneto-optical effects as optical elements in the soft x-ray, can be found in ref. 5.

Magnetic contrast in the microscope results from the same MCD effect operative in the circular polarizer. A test of the available contrast was made using two saturated Fe films of equal (26 nm) thickness. The upstream film (in the polarimeter) was set with 45° incidence angle, and the downstream film (in the STXM) with 55° incidence angle. Transmission spectra were measured across the $L_{2,3}$ edges through the two films in different settings, with the magnetizations nominally parallel and antiparallel, by reversing the sign of M in the upstream film. Figure 2 shows the resulting absorption spectrum of both measurements. A significant difference between the two curves is seen at the peak of the L_3 line. When $k \cdot M$ for each film has the same sign, the net absorption is greater than for opposite signs, producing a maximum difference in absorption product μt of about 15 percent between these two settings for this film thickness. The difference in transmitted intensity for these films is nearly 20 percent, setting the maximum contrast for these specific conditions. Somewhat more than 10 percent of the incident flux is transmitted through both polarizer and sample at the L_3 line, and the transmitted flux is of order 10^6 photons per second, providing adequate signal-to-noise at 50-100 msec dwell times to image domains with this contrast.

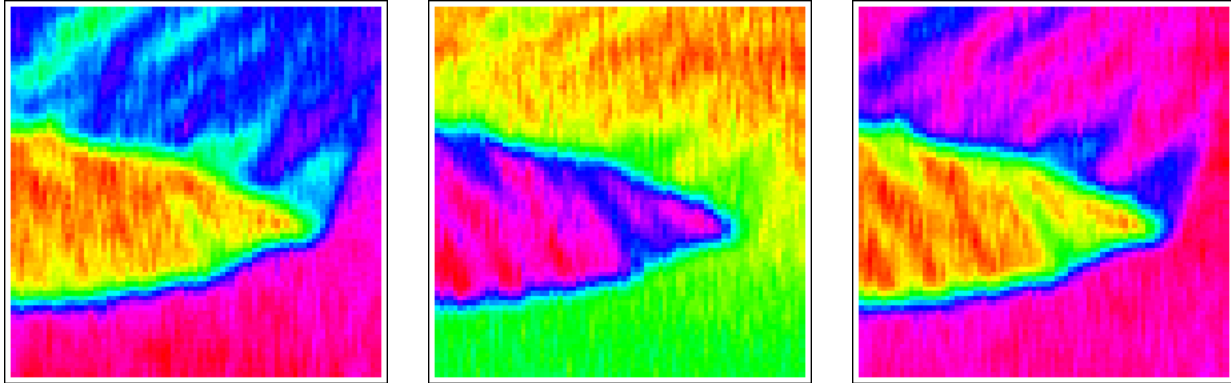


Figure 3. A needle-shaped domain pointing toward the right is surrounded by a larger domain with opposite magnetization in a demagnetized 20 Fe film. All images show the same 40 x 40 μ field. Images at left and center are taken with + and - helicity, respectively, while that at right is the divided image +/- . In addition to the two prominent 180° domains, each domain shows regular fluctuations in magnetization with distinct spatial relationships, presumably associated with the growth of the small domain into the other.

EARLY DOMAIN IMAGES FROM DEMAGNETIZED IRON FILMS

Early magnetic domain images using these techniques were obtained from Fe films and are shown in Figure 3. This 20 nm thick demagnetized film exhibited a needle-shaped domain, with \mathbf{M} nominally along needle axis, extending into a large region of film with opposite magnetization. The three images in Fig. 3 all show the same 40 x 40 μ field. The image at left was obtained with + helicity and that at center was obtained with - helicity. At right is the divided image of +/- helicities. In addition to the needle shaped domain pointing to the right, weak features are observed both within the needle domain and above it in the surrounding domain. In each case these weak features are regular fluctuations in magnetization inclined at an angle to predominant direction of \mathbf{M} in each domain. In the two different domains these fringes are oriented at nominally 90° to each other in the film plane. These fluctuations in magnetization, even though observed in static images, are presumably related to the dynamics of domain wall motion since the domains result from a demagnetization process. These transmission images are effectively direct maps of $\mathbf{k} \cdot \mathbf{M}$ projected through the sample, and thus can provide quantitative magnetization maps, especially when aided by multiple angle viewing. Continued analysis and experiments are investigating if these fluctuations are associated with just the interface regions of the films (which seems likely), or if they extend throughout the films.

CONCLUSIONS AND FUTURE DIRECTIONS

Early transmission imaging results in a scanning transmission soft x-ray microscope reveal complementary capabilities to previously demonstrated x-ray techniques for imaging magnetic domains, and point toward future applications and improvements. Working in transmission clearly allows the bulk of thin film structures to be investigated, rather than just near surface features as in electron imaging microscopes. This penetrating ability will allow imaging of magnetization distributions in different magnetic layers of magnetic multilayer structures. Compared to the imaging x-ray microscope [3] which uses only the zone plate to achieve energy resolution, the the grating monochromator associated with the STXM allows high resolution spectroscopy as well as magnetic contrast. This should aid in quantifying observed

magnetization variations, and also allow study of chemical inhomogeneities that might manifest themselves through different spectral (and magnetic) features near absorption edges. Continuing activities combining these features are currently aimed at quantitative imaging of magnetization distributions in individual magnetic layers of magnetic multilayers, where the element-specificity of soft x-ray techniques provides unique capabilities to observe domains in a magnetic layer buried underneath other magnetic layers. Such capabilities are of interest both for fundamental studies of magnetic correlations in coupled systems and to characterize technologically relevant structures such as spin valves, where understanding the magnetization behavior in buried layers presents experimental challenges.

Many improvements can be envisioned to make these transmission techniques more sensitive and useful. Spatial resolution of the probe spot in these early images is not better than 150 nm, and should improve perhaps to 50 nm in the future. In situ studies of domain reversal processes will be possible with a coil around the sample. Use of Faraday rotation, just below the L_3 white lines, as a contrast mechanism will allow thicker samples to be studied in transmission. It should be possible to develop a reflecting microscope sensing Kerr rotation with significant depth penetrating ability to allow study of magnetic structures on opaque substrates. The variable polarization of the upcoming elliptically polarizing undulator will enhance the contrast and capabilities of such microscopes considerably.

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Principal Investigator: Jeffrey Kortright, Materials Sciences Division, Lawrence Berkeley National Laboratory, Email: jbkortright@lbl.gov, Telephone: 510-486-5960.